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NEW TECHNIQUES FOR THE
ANALYSIS OF MANUAL CONTROL SYSTEMS

FINAL TECHNICAL REPORT

George A. Bekey

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Department of Electrical Engineering
University of Southern California

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INTRODUCTION

The purpose of this grant has been to apply modern techniques of system identification to the study of human operator behavior in manual control systems. The results of this study have been published in 10 technical progress reports, 8 publications in scientific journals and 4 presentations to the scientific community at various conferences. Four Ph.D. students at the University of Southern California have based their research and dissertations efforts on this study. Abstracts from all these papers have been included as part of this final technical report.

The major objective of the studies is the application of advanced analytical and computational methods to the development of mathematical models of human controllers in multiaxis manual control systems. Our emphasis has been on the study of adaptive and nonlinear phenomena. More specifically, we have been involved in projects in the following areas.

1. The development of analytical and computer methods for the measurement of random parameters in linear models of human operators. The mathematical basis of the technique has been developed and its application to a simple human controller model demonstrated [7].*

2. Discrete models of human operator behavior in a multiple display situation have been developed [5]. The unusual modeling technique has been based on the introduction of novel model elements to represent decision processes. The feasibility of the

*Refers to page number of abstract.

of the technique has been demonstrated in a two display, single controller task, using widely separated displays requiring significant eye movements. [5, 23]

3. Sensitivity techniques have been developed which make possible the identification of unknown sampling intervals in linear systems [14]. This technique has been applied to the identification of sampling frequencies in sampled data models of human controllers. [10, 18, 19, 26]

4. The adaptive behavior of human operators following particular classes of vehicle failures has been studied and a model structure proposed [15]. The details of the learning process preceeding such a failure have been investigated. [8, 13, 16, 20, 25]

Furthermore, the following specific technical objectives have been:

1. Further investigation of the application of sampled data theory to manual control systems, with emphasis on multi-axis control.

2. The application of modern filtering and control theory to the determination of manual controller behavior in tasks where both observation and measurement are contaminated by noise. [5]

3. Further study of the application of gradient methods to the study of adaptive behavior of human controllers, with emphasis on the relation between stability and adaptation.

4. The application of hybrid computer techniques to the study of manual control systems, where human decision functions are

modeled by digital computers and control system dynamics are represented by analog computers. [5,17,22]

PROGRESS REPORTS

Research On New Techniques for the Analysis of Manual Control Systems

George A. Bekey

- No. 1 June 15, 1965 - December 15, 1965.
- No. 2 December 15, 1965 - June 15, 1966.
- No. 3 June 15, 1966 - December 15, 1966.
- No. 4 December 16, 1966 - June 16, 1967.
- No. 5 June 16, 1967 - December 15, 1967.
- No. 6 December 15, 1967 - June 15, 1968.
- No. 7 June 15, 1968 - December 15, 1968.*
- No. 8 December 15, 1968 - June 15, 1969.†
- No. 9 June 15, 1969 - June 15, 1970.
- No. 10 June 15, 1970 - June 15, 1971.††

* with Michael J. Merritt

† with Michael J. Merritt and Anil V. Phatak

†† with Anil V. Phatak

DISSERTATIONS

D1	Merrit	1967
D2	Brainin	1966
D3	Phatak	1968
D4	Neal	1968

D1

Merritt, M. J., "Synthesis and identification of mathematical models for the discrete control behavior of human operators," University of Southern California, Electronic Sciences Laboratory, USCEE Report 202, May 1967.

ABSTRACT

This report describes the synthesis and identification of mathematical models which characterize the discrete control behavior of human operators. This type of behavior occurs in control situations where the human operator must decide between a small number of alternatives, while generating continuous control actions at the same time. Models of this type have been proposed previously; however, systematic techniques for their synthesis and identification have been lacking. In this report a systematic treatment of discrete control actions is made possible by the introduction of two new elements which can be used to configure complete human operator models.

Two types of hybrid elements are presented. One accepts continuous inputs and produces binary outputs, while the other has continuous inputs and produces continuous outputs under the control of binary signals. Decisions to initiate an action, throw a switch, or select which switch out of a group of switches should be operated are described by a Multi-State Decision Element (MSDE). Decisions concerning the magnitude of a discrete control action, the length of a control interval, etc., are modeled by a Proportional Decision Element (PDE).

Procedures and digital computer programs for the complete identification of both types of elements are given.

The Multi-State Decision Element and the Proportional

Element are applied to the modeling of human operators performing compensatory tracking of gaussian random inputs. Two experiments were performed. The basic control task was the same in both cases. The controlled element resembled the pitch axis of an aircraft and was selected in such a manner that pulsatile control actions were generated by the operators.

In the first experiment, the operator viewed a single compensatory oscilloscope display, which presented altitude error. A Multi-State Decision Element was used to model the operator's decision to initiate a pulsatile control event. A Proportional Decision Element was used to model the operator's decision as to the amplitude and width of the pulse event. The elements were completely identified and resulted in an asynchronous input dependent sampled data model of the human operator's control actions.

The second experiment was an extension of the first, in which the resemblance to an aircraft stick axis was enhanced by adding an attitude display presenting pitch angle. The operator's control behavior consisted of pulsatile stick motions and eye motions between the widely separated attitude and error displays. A complete human operator model, describing both stick motion and eye motion was constructed using the two decision elements. The resultant model contains a deterministic input dependent decision element modeling the operator's eye motions.

D2

Brainin, S.M., "The estimation of randomly varying parameters in linear systems", Ph.D. Dissertation, University of Southern California, Department of Electrical Engineering, June 1966.

ABSTRACT

This dissertation describes the formulation and development of an approach to the identification of linear dynamic systems with random parameters. A technique, based on the Fokker-Planck partial differential equation, is developed for estimating the statistics of randomly varying parameters in systems whose differential equation is known a priori. The resulting mathematical model then applies to a family of similar systems rather than to an individual system.

The identification of a single random parameter in a first-order linear system was made in two controlled series of experiments in order to determine the accuracy of the method. In this application, minimization of a suitable criterion function was made both by a continuous steepest descent, and by a discrete regression algorithm.

The technique was then applied to identification of a two parameter model of a human operator, performing a tracking function. The statistics of both parameters were determined and the validity of the identification discussed.

Finally, the application to higher order linear systems, nonlinear systems and systems with transport delays are discussed, and proposals are made for future research in these areas. The latter two cases are illustrated by examples.

D3

Phatak, A. V., "On the adaptive behavior of the human operator in response to a sudden change in the control situation", Ph.D. Dissertation, University of Southern California, Department of Electrical Engineering, June 1968.

ABSTRACT

This dissertation presents the synthesis of a mathematical model which describes the adaptive behavior of a trained human operator in response to sudden changes in plant dynamics and transient disturbances. The operator performs closed-loop manual control in a compensatory tracking situation and is trained to adapt to a finite number of alternative transitions in plant dynamics. These plant changes are so chosen as to result in overall system instability unless the operator rapidly modifies his tracking strategy to that required for the new dynamics.

There are a number of practical ways in which the plant dynamics may change suddenly. The example studied in this investigation is that of an aircraft whose stability augmentation may fail. Data were taken in a series of fixed base simulation experiments where the operator was instructed to track (keep wings level) a single-axis roll control task of a VTOL aircraft in hover. The basic airframe is approximately a pure inertia and has rate and attitude feedback augmentation for increased stability. The failure of the rate sensor and/or the attitude sensor results in a sudden transition in the gain and order of the effective plant dynamics. These failures may be accompanied by transients in either of the two feedback outputs. The operator was not given any details about the plant dynamics, types of failures or any other information which would tend to bias his control strategy.

Based on experimental data for human operator response to various types of failures the operator adaptive strategy was partitioned into four distinct phases:

Prefailure steady state control

Detection of failure or change in plant dynamics

Identification of post-failure plant dynamics and appropriate modification of his control strategy

Post-failure steady state control

The synthesis of an adaptive model of the operator which includes the decision processes involved in going sequentially through the four phases is presented. The model incorporates a higher level controller called a Supervisor. The supervisory control algorithm is completely identified. Detection of a change in plant dynamics is based on the course of the error phase trajectory following failure. Identification of post-failure dynamics is sequential in nature and dependent on pattern recognition of the error-error rate trajectory in the phase-plane. Actual operator data was used to obtain these patterns for detection and identification.

Finally the adaptive supervisory model suggested has a variable structure, contains mode switching based on pattern recognition as evidence and incorporates the decision-control strategy or algorithm used by a trained operator.

D4

Neal, C.B., "Estimation of the parameters of sampled-data systems by means of stochastic approximation", Ph.D. Dissertation, University of Southern California, Department of Electrical Engineering, December 2, 1968.

ABSTRACT

Various methods have been proposed to estimate the parameters of both open loop and closed loop sampled-data control systems. Generally speaking, these methods yielded approximate models of the system under study; the degree of approximation depending on the a priori knowledge of the system structure, state observation noise, system nonlinearities, and other factors. However, none of the methods has been applied to the problem of determining the sampling interval of either closed loop or open loop sampled-data control systems. This has been the task of the present study. Specifically, this dissertation is concerned with estimation of parameters in systems which have internal sampling, but have continuous input and output. The continuous portion of the sampled-data system is given by the differential equation

$$\frac{dz}{dt} = f(z, p, u(t)); z(t=0) = \xi$$

where z is an n dimension vector of state, $f(\cdot)$ is the n dimensional vector of the dynamical system, p is a constant h dimensional vector of parameters, $u(t)$ is an r dimensional vector of piecewise continuous control functions, and ξ is the initial condition vector. For our results, $f(\cdot)$ was required to be of class C^1 in z and p . The differential

equation is preceded by some form of data hold. The model-matching technique was used for parameter estimation. Methods were developed for determining not only the sampling interval, but all the other parameters and initial conditions of the sampled-data system as well.

In this investigation, three methods were employed for the estimation of sampling intervals and other parameters of a sampled-data system. In all methods, the cost function was the integral of norm-squared error, where the error function was defined as the difference between the observed state vector of the system, and the state vector of the model.

The first method employed programmed search to vary the model parameters in order to minimize the cost function.

The second method employed iterative gradient search by means of discrete sensitivity difference equations for the various model parameters. The work of Bekey and Tomovic in connection with discrete sensitivity difference equations for the sampling interval was extended to all the other parameters of the system. Gradient search was then used for the parameter estimates.

The third, and most important, method used that of stochastic approximation. This permitted observation noise. The mean-square convergence of the model parameters to the true parameters of the system was proved under the following conditions: The system and model agreed in form and order, the data holds were identical, the observation noise had zero mean, finite variance, and was uncorrelated with both the system state vector and model state

vector, $f(\cdot)$ was of class C^1 in z and p , and the partial derivative of the cost function with respect to the sampling interval existed and was bounded.

Stochastic approximation was then applied to the practically important problem of estimating the parameters of the human operator from records of scalar input and scalar output of the human operator operating in a closed loop configuration. Parameters were estimated successfully in both continuous and sampled-data models of human operators.

PUBLICATIONS

P1	Angel and Bekey	1968
P2	Bekey and Neal	1968
P3	Phatak and Bekey	1969
P4	Phatak and Bekey	1969
P5	Coggshall and Bekey	1970
P6	Coggshall and Bekey	1970
P7	Neal and Bekey	1970
P8	Bekey	1970

P1

Angel, E.S., G.A. Bekey, "Adaptive finite-state models of manual control systems", IEEE Transactions on Man-Machine Systems, Vol. MMS-9, number 1, March 1968, pp.15-20.

ABSTRACT

A model of human operator behavior is presented based on the following assumptions: that the input and output are quantized into a limited number of states and that data processing is performed on asynchronous samples of this coarsely quantized input, i.e., that the human operator behaves as a finite-state machine. A hybrid element or hybrid actuator is used to achieve a continuous variation of output position.

P2

Bekey, G.A., C.B. Neal, "Identification of sampling intervals in sampled-data models of human operators", IEEE Transactions on Man-Machine Systems, vol. MMS-9, Number 4, December 1968, pp.138-142.

ABSTRACT

The synthesis of sampled-data models of human controllers has been hampered by the lack of systematic procedures for estimating the sampling frequency to be used in the model. This paper presents two methods (programmed search and gradient search) for the determination of an unknown sampling frequency in closed-loop sampled-data systems. Both methods are based on a priori knowledge of the structure of the system to be identified and require only measurements of the continuous input and output of the system.

Several theorems concerning the identification problem are presented. The application of both the gradient search and programmed search techniques is illustrated by several examples.

P3

Phatak, A.V., G.A. Bekey, "Model of the adaptive behavior of the human operator in response to a sudden change in the control situation", IEEE Transactions on Man-Machine Systems, Vol. MMS-10, Number 3, September 1969, pp.72-80.

ABSTRACT

An adaptive model is presented to describe the behavior of the human operator in response to sudden changes in plant dynamics and transient disturbances. The plant simulated for tracking experiments is approximately second-order and has rate and attitude feedback augmentation for increased stability. The failure of the rate sensor and/or the attitude sensor results in a sudden transition in the order and gain of the effective plant dynamics. These failures may be accompanied by hard-over transient conditions in either the rate or attitude sensors. The adaptive model suggested has a variable structure, contains mode switching based on pattern recognition as evidence, and incorporates the decision-control logic required for successful adaptation to failures. The model in effect attempts to mimic the control strategy or algorithm used by a trained operator.

P4

Phatak, A.V., G.A. Bekey, "Decision processes in the adaptive behavior of human controllers", IEEE Transactions on Systems, Science and Cybernetics, Vol. SSC-5, No. 4, October 1969, pp. 339-351.

ABSTRACT

A decision algorithm which simulates the rapid adaptive behavior of human controllers following sudden changes in plant dynamics is developed. The control of a VTOL aircraft in hover following failure of the stability augmentation system is used as a specific example. The decision algorithm is based on the assumption that the human controller recognizes certain pattern features in the error/error-rate phase plane. Experimental data, obtained from pilots facing four possible alternatives following the time of failure, are presented. The proposed decision algorithm is developed, and digital simulation results are discussed. A theoretical justification for the algorithm, based on statistical decision theory, is presented.

P5

Coggshall, J.C., G.A. Bekey, "EMG-force dynamics in human skeletal muscle", Med. & Biol. Engng, vol. 8 (1970) pp.265-270.

ABSTRACT

An on-line parameter tracking algorithm, implemented on an analog computer, is used to obtain parameter values in an assumed mathematical relation between the full-wave rectified EMG and the force produced by the human triceps muscle in an isometric task. The relation between the actual force produced by human subjects and the computed force predicted by the model is discussed.

P6

Coggshall, J.C., G.A. Bekey, "A stochastic model of skeletal muscle based on motor unit properties", Mathematical Biosciences, vol. 7 (1970), pp. 405-419.

ABSTRACT

The properties of individual motor units are used as the basis for the formulation of a mathematical model of force generation by skeletal muscle. Using unknown data from cat motor units and with the assumptions of linearity and that twitch initiations obey a Poisson distribution, the dynamic force response of a whole muscle is calculated and compared with published experimental data.

P7

Neal, C.B., G.A. Bekey, "Estimation of the parameters of sampled-data systems by means of stochastic approximation", Int. J. Systems Sci., vol. 1, 1970, pp.63-74.

ABSTRACT

This paper discusses the application of stochastic approximation to the estimation of sampled-data system parameters, including the sampling interval. The sampled-data systems considered have a closed-loop configuration, continuous input and output signals and error sampling. A continuous dynamic system follows a zero-order hold. Sufficient conditions are given for the mean-square convergence of a stochastic approximation algorithm of the Kiefer-Wolfowitz type which is used to estimate all the parameters of the sampled-data system.

Simulation results are presented which illustrate the theoretical results. In addition, simulations indicate that good estimates of the mean values of parameters are still possible when the parameters have random components.

P8

Bekey, G.A., "The human operator in control systems" In: Systems Physiology (K.B. DeGreene, ed.) McGraw-Hill Book Company, New York, 1970.

Also published in: Systems Behavior, J. Beishon and G. Peters, ed., Harper & Row, Publishers, New York, 1972.

ABSTRACT

This chapter surveys the role of man as an element or constituent in a control system. Such systems include the steering of an automobile, manual attitude control of a spacecraft, the control of piloted aircraft, manual process control, air traffic control, and, in certain cases, man-computer systems. The ultimate responsibility of the human element in a man-machine system is to take action that influences the system. The automobile driver receives inputs from the road ahead, from his instruments, from the sound of the engine, from the acceleration forces on his body, and so forth. He processes all this information to arrive at decisions regarding appropriate actions. Finally, he must act—by braking, turning the steering wheel, accelerating, or perhaps by some combination of these actions. This action is the man's control input to the machine. Thus control may be viewed as the end product of a chain of processes, which begin with information processing and continue through decisions.

The relation between information theory, decision theory and control theory may be viewed from a mathematical point a view. Thus, a decision to act may be viewed from the standpoint of ultimate utility to the human controller. The relevant mathematical disciplines here are value theory or utility theory. On the other hand, a decision may

be viewed from the standpoint of maximizing the information transfer through a system. The relevant dimension of decision theory here would be the probability theory. Finally, the decision to act, in the presence of uncertainty, may be constrained by system stability considerations, in which case the relevant discipline is control theory.

In the past information theory, decision theory and control theory have been developed as separate disciplines. Only now is control theory beginning to use the available tools in the other disciplines. Thus, interest is beginning to focus on the adaptive and decision making behavior of human controllers in complex systems.

In this chapter, we first introduce some of man's input-output characteristics that are important to the design of man-machine systems. The psychological and engineering approaches to the description of man as a control element are then discussed. Display and control factors are reviewed briefly, with some examples of actual and proposed systems. The engineering approach to control systems is then indicated, and some mathematical models of the human operator's function are presented. Finally, simulation of manned systems is examined briefly in terms of stimuli, experimental design and evaluation criteria.

CONFERENCE PROCEEDINGS

C1	Bekey and Angel	1966
C2	Bekey, Biddle, Jacobson	1967
C3	Phatak and Bekey	1969
C4	Neal and Bekey	1969

C1

Bekey, G.A., E.S. Angel, "Asynchronous finite state models of manual control systems", Proceedings 2nd Annual Conference on Manual Control (NASA SP-128), 1966, pp.25-37.

ABSTRACT

The mathematical models most commonly used to represent human operator behavior in manual control systems are based on the assumption that the operator observes and makes use of a continuum of input states. In contrast to those approaches, this paper is based on the assumption that the operator quantizes his input and output into a limited number of states and that data processing is performed on asynchronous samples of this coarsely quantized input; that is, the human operator behaves as a finite-state machine. A hybrid output element or hybrid actuator is used to achieve a continuous variation of output position.

In order to provide for the generation of timed output waveforms in manual tracking, the paper shows that the concept of the hybrid actuator also provides a bridge between binary decisions and continuous time. The application of standard logical design techniques to the synthesis and minimization of the resulting mathematical models is discussed. It is shown that for the particular case of compensatory control of a pure inertia plant, a human controller model can be synthesized by using only threshold gates, flip-flops, gates, and hybrid actuators.

The paper concludes with a discussion of proposed research in further applications of finite-state machine theory to manual control.

C2

Bekey, G.A., J.M. Biddle, A.J. Jacobson, "The effect of a random-sampling interval on a sampled-data model of the human operator", Proceedings, 3rd Annual Conference on Manual Control (NASA SP-144), 1967, pp.247-258.

ABSTRACT

There are a number of proposed mathematical models of the human operator in a compensatory tracking function. Some features of a human operator, such as time delay, have been relatively easy to incorporate in most of these models. However, the remnant, or those frequencies in the human operator's output which are not linearly correlated with the input, has never been easy to include in a satisfying, organic fashion in many of the models. In recent years, sampled-data models have been advanced for a number of reasons, one of which is that such models will produce naturally frequencies not present in the input due to the presence of the sampler.

Historically, sampled-data models of the human operator have assumed a periodic sampler. The behavior of such samplers has been studied extensively and certain characteristic features have been well described. For instance, if the model contains such a sampler, the output spectra will have "humps" containing direct and reversed images of the input spectra centered about integral values of the sampling frequency. In addition, there is a null point in the output spectra at each integral value of sampling frequency rather like a deep valley between two hills.

It has been reported that carefully analyzed records of actual human-operator outputs failed to show the humped spectra

characteristic of a periodic sampler. In that report, the authors theorized that the remnant is due to time-varying parameters, such as gains, time constants, and time delays within the human-operator transfer function. If these parameters may vary, how would the behavior of a human operator model be affected if, assuming it contained a sampler, the sampling interval were allowed to vary in some fashion? Our experiment is an investigation of a sampled-data human-operator model in which the sampling interval varies randomly about some mean value.

C3

Phatak, A.V., G.A. Bekey, "On modelling the adaptive characteristics of human controllers", Proceedings of a Conference on Applications of Continuous System Simulation Languages, San Francisco, 1969, pp.159-193.

ABSTRACT

This paper presents the development of a decision-control algorithm which models the rapid adaptive response of human controllers following sudden catastrophic changes in plant dynamics. The specific control task chosen is that of manually controlling the roll axis of a simulated VTOL aircraft in hover following failures in the stability augmentation system. The decision algorithm is based on the assumption that the human controller is trained to recognize certain pattern features in the error-error rate trajectory. Actual human operator response data are used to identify the decision-control logic incorporated in the proposed algorithm. Finally, results from digital simulations of the proposed adaptive controller model in various failure situations are discussed.

C4

Neal, C.B., G.A. Bekey, "Identification of human operator models by stochastic approximation", Proceedings of Fifth Annual NASA-University Conference on Manual Control, 1969, pp.3-20.*

ABSTRACT

This paper discusses the application of stochastic approximation to the estimation of human operator model parameters. Both continuous and sampled-data models are considered. Stochastic approximation was used successfully for parameter estimates in both types of models. In the case of sampled data models, all parameters, including the sampling interval, have been estimated.

* Also published in Mathematical Biosciences 10(1971) pp.91-116.